

Creating the Required Deep Space Environments for Testing the James Webb Space Telescope (JWST) at NASA Johnson Space Center's Chamber A

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Abstract

NASA is the mission lead for the James Webb Space Telescope (JWST), the next of the “Great Observatories”, scheduled for launch in 2021. NASA was directly responsible for the integration and test (I&T) program that culminated in an end-to-end cryo vacuum optical test of the flight telescope and instrument module in Chamber A at NASA Johnson Space Center. Historic Chamber A is the largest thermal vacuum chamber at Johnson Space Center and one of the largest space simulation chambers in the world. Chamber A has undergone a major modernization effort to support the deep cryogenic, vacuum and cleanliness requirements for testing the JWST.

This paper will discuss the thermal vacuum test of the Optical Telescope Element (OTE) plus Integrated Science Instrument Module (ISIM) (OTIS) as well as the extensive series of tests that were performed to incrementally validate the operations and performance of the Chamber and Ground Support Equipment (GSE). Each test required a unique thermal vacuum profile for cool down and warm up, steady state operations, GSE testing and contamination control. Select results will be presented on Facility Functional Testing, Chamber Bake-out, GSE Cryo-Proof Testing, Chamber Commissioning, the Optical Ground Support Equipment (OGSE) Test series and the final thermal vacuum test of the OTIS with respect to facility operations to meet JWST program test requirements.

Introduction

NASA Johnson Space Center's Chamber A was built in 1963 to test the Apollo Command Module as part of the nation's race to the moon. Today, Chamber A is still a vital part of testing marquee spacecraft like the optical portion of the James Webb Space Telescope (JWST). The successful cryo-vacuum test of the Optical Telescope Element (OTE) plus ISIM (OTIS) portion of the JWST in the summer of 2018 owes much of its success to a series of test from 2012 through 2017. The JWST test series provided the opportunity to verify and practice critical operations and systems. The entire test series in support of JWST can be broken into three distinct testing phases; Facility and Ground Support Equipment (GSE) Checkouts, Thermal Pathfinder (PF) and finally OTIS Cryo-Vacuum.

JSC tests in support of JWST OTIS	Steady state Temp (K)	Steady state Pressure (Torr)	Duration (days)
2012 – Facility Functional #1	12	10^{-7}	19
2013 – Facility Functional #2	19	10^{-7}	9
2014 – USF Cryo Proof Load	13	10^{-7}	7
2014 – Bakeout	298-332	10^{-4} - 10^{-6}	25
2014 – Chamber Commissioning and GSE C/O	17	10^{-5} - 10^{-7}	41
2015 – Pre-Pathfinder Vacuum Functional	298	10^{-5}	5
2015 – PF OGSE1	31	$*10^{-3}$	33.5
2015 – PF OGSE2	32	$*10^{-3}$	35.3
2016 – Thermal Pathfinder	20	10^{-7}	52.7
2017 – Pre-OTIS Vacuum Functional	298	10^{-5}	4.5
2017 – OTIS Thermal Vacuum Test	20	10^{-7}	102

*Helium backfill

Table 1: JSC Tests Series in Support of JWST

Acronyms

AFMS	Air Flow Management System
GSE	Ground Support Equipment
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope
K	Kelvin
KW	Kilowatt
LN2	Liquid Nitrogen
NASA	National Air and Space Administration
OGSE	Optical Ground Support Equipment
OTE	Optical Telescope Element
OTIS	Optical Telescope Element (OTE) plus ISIM
PF	Pathfinder
UHP	Ultra-High Purity
USF	Upper support Frame

Facility and GSE Checkouts

To support the unique testing environment needed to test the JWST's optics, Chamber A went through major modifications to many key systems as well as the integration of unique GSE. The high vacuum and liquid nitrogen (LN2) delivery systems were both heavily modified and a new 12.5KW helium refrigeration plant was added, all of which are key facility components needed to create the deep space environment. Before critical flight hardware was tested, the test team performed a series of five tests to gain the needed operational experience on the GSE and new facility systems. The first two tests were facility functionals to verify and shake down the new systems. Following the facility functionals were the Upper Support Frame (USF) Cryo-Proof load test, a chamber bakeout and finally the Chamber Commissioning and GSE checkout.

Facility Functional – 2012

In the summer of 2012, the major chamber modifications were complete and the first of the two functional tests was performed. This presented the first opportunity when all modified systems were working together

to establish vacuum conditions inside Chamber A. The goal of the initial functional was to create a baseline performance of the chamber capabilities. After 19 days of testing, the results were very promising. The initial pumpdown, shown below in Figure: 1, shows the chamber pressure and the temperature of the LN2 shrouds, as well as the helium shroud average without any limits or constraints to the rates.

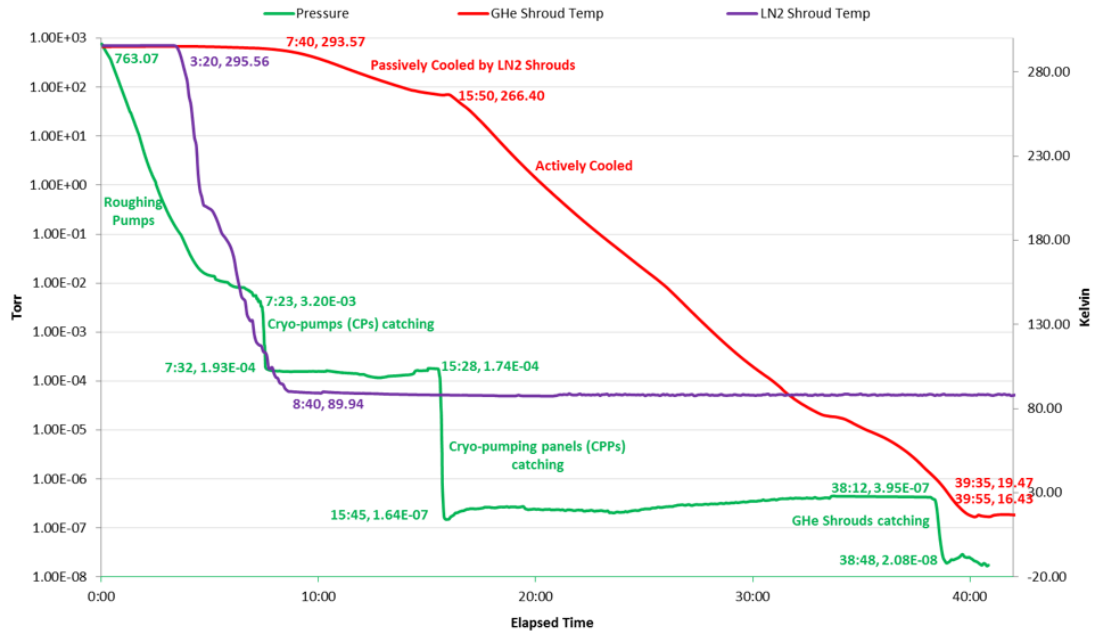


Figure 1: Facility Functional Chamber Pumpdown and Cryogenic Operation¹

The legacy roughing system and the newly modified high vacuum system, 12 cryopumps and 6 turbopumps, lowered the chamber pressure to 2×10^{-4} Torr in a little under 8 hours. Shortly after initial pumpdown, the new LN2 thermal syphon system was activated to cool the helium shrouds to 90K. Once the LN2 and vacuum systems were in a steady state, the helium systems were cooled. Simultaneously a legacy 3.5KW helium refrigeration plant started to cool cryopumping panels within the chamber while the larger 12.5KW plant cooled the main chamber shrouds. As the much smaller cryopumping panels cooled to the point of freezing out nitrogen and oxygen, the chamber pressure followed suit stabilizing around 4×10^{-7} Torr while the main shrouds continued to cool to about 20K. Forty hours after pumpdown began, the chamber was at a steady state of 2×10^{-8} Torr, 90K on the LN2 shrouds and 20K on the main helium shrouds.

In addition to the new system checkouts, the 2012 functional provided the opportunity to perform additional checkouts and characterizations. A bakeout was performed where the helium shrouds were warmed to 335K and the pressure held at 1×10^{-1} Torr. The last half of the test was dedicated to checkout out an uncontrolled helium shroud warmup as a result of a total power outage. With the chamber at high vacuum and the helium shrouds at 15K, power to the entire facility was isolated. The high vacuum systems and associated support systems maintained the chamber pressure for about a day before restoring normal power and continuing testing. The final operational check out was of the GN2 repress system. To limit contamination, the chamber repress was limited to no greater than one Torr/min.

Facility Functional – 2013

The following summer, the Chamber and test team were ready for the next facility functional. Similar to the functional performed in 2012, the objective this thermal-vacuum functional test was to demonstrate basic chamber functionality and perform a complete chamber leak check. Once the Chamber environment was at a steady state, 10^{-7} Torr and 20K helium shrouds, a very thorough helium leak check was performed. This leak test was the baseline that all future tests would follow by establishing pretest checks of all dynamic seals and hatchways as well as a configuration control management system for the over 200 penetrations on the Chamber. In addition to the leak checks, this test was used to check out potential backup systems. For

example, in the event there was a problem with the turbopump backing pumps, it was proved that a simple portable turbopump pump cart was an adequate substitute to the standard backing system once at steady state.

USF Cryo-Proof Load test – 2014

Up to this point, both of the functional tests focused primarily on the Chamber and the operations to create the needed space environment. The USF Cryo-Proof Load Test, was the first test to be driven specifically by the JWST test requirements to checkout and verify new GSE. The primary objective was to induce thermal gradients in the USF by having a temperature delta between the conductively cooled top of the frame to the insulated bottom of the frame. Following the cooldown profile provided by the OTIS test team, the helium shrouds were cooled to an average temperature below 20K. This was the first time the cooldown rate was dictated by real time analysis. Using the 12.5KW helium Train 3, the operators were able to make real time adjustments to match the desired profile. This ability to make adjustments as small as half a kelvin would be a key factor in maintaining hardware safety for just about every test going forward. Once the USF and new GSE had completed their objectives, the helium shrouds followed the provided warm-up profile. This profile called for a new capability in the form of an ultra-high purity helium (UHP) backfill to aid in the warming of the hardware and to support thermal model development. To achieve the desired pressure, helium was added to the chamber volume through a small metering valve and then balanced by the turbopumps at the specific pressure. When the backfill was complete, the UHP helium was isolated and the Chamber returned to high vacuum.

Bakeout – 2014

Shortly after the USF test, the Chamber went through a bakeout to off-gas volatile molecules from the GSE and facility surface material that would be used in future testing of JWST critical flight and optical systems. Following a typical pumpdown using the roughing and high vacuum systems, the OTIS contamination control team performed an initial off-gassing measurement. Once the contamination team had their baseline measurement, two new 7.5m² LN2 scavenger panels were conditioned to 90K and were to remain cold until repress. To prevent contamination of the cryopumps, all 12 cryopumps were isolated leaving just the turbopump system to maintain chamber pressure while both nitrogen and helium shrouds were warmed to 333K. After 17 days, the shrouds cooled back to ambient temperature so a new off-gassing measurement could determine the progress of the bakeout and then warmed back to 333K. After an additional 5 days at 333K, the final off-gassing measurement showed acceptable off-gassing levels and the bakeout was complete. To prevent any of the residue from being released back into the chamber both LN2 scavenger panels were maintained below 120K during the initial repress. At 400 Torr, the scavengers were isolated from the LN2 supply and allowed to warm as the chamber continued to repress. Post-test analysis by the JWST contamination control team showed a reduction in overall off-gas rates by a factor of greater than 50.

Chamber Commissioning and GSE Checkout – 2014

The final test before the Pathfinder test series was the official Chamber commissioning which took place in the fall of 2014. The primary goal of the commissioning test was to verify the facility was capable of meeting or exceeding the unique requirements laid out by the JWST program. Ultimately, the Chamber Commissioning provided some of most valuable lessons in preparation for JWST hardware. The ultimate pressure achieved on the initial pumpdown was 0.48 Torr, preventing any attempt at crossing over to the high vacuum system. Through a coarse leak check, the test team identified a large-scale leak associated with a pressure-tight enclosure housing some GSE. At this point, the Chamber was repressed to attempt a fix the leak. The second pumpdown attempt was marginally better but again prevented a crossover to high vacuum. The Chamber was brought back to ambient conditions and again a temporary fix was attempted.

After the second attempt at a fix, the Chamber was able to cross over to the turbopumps at 17×10^{-3} Torr but the gas load, ~70 Torr-l/second, was too much for the cryopumps. To overcome the gas load the LN2 shrouds were conditioned to 90K and a single panel of the legacy cryopumping panels was conditioned to 20K. This additional pumping capacity was enough to fully crossover to the high vacuum system. To counter the radiative cooling of the LN2 shrouds, warm helium was circulated through the helium shrouds so ambient temperature GSE checks could be accomplished.

Once the GSE checkouts were complete, cooling of the helium shrouds began. When the helium shroud average temperature was 50K, a helium backfill was activated to hold the chamber pressure at about 5×10^{-3}

to help cool the GSE that was not actively cooled. Once the GSE had achieved the cooldown requirements, the helium backfill was isolated and the chamber transitioned to a steady state of 5×10^{-7} Torr and 17K on the helium shrouds. While at cryo-stable conditions, the GSE team went through their test points and the facility team was able to verify the chamber requirements.

While at cryo-stable conditions, the impact of the leak at the top of the chamber became apparent in the form of visible air and water frozen out over the 12 days the helium was at 17K. The visible 'ice', shown below in Figure 2, on the outer side of the helium shrouds really made clear the need to minimize the leak rate of the chamber.



Figure 2: Visible Air Ice on Helium Shroud Piping

The amount of frozen air that needed to be released would make the helium shroud warmup a delicate balance to maintain hardware safety. Warming too fast could cause a rapid increase in pressure, which could damage some of the sensitive hardware due to a sudden thermal coupling to the colder elements in the chamber. To achieve the safe release, the helium shrouds were gradually warmed until the pressure maximum was reached while making helium temperature adjustments to maintain that pressure with both roughing and turbopumps open to the chamber. When the pressure started to decrease more heat was added and vice versa, the helium supply temperature would be dropped until the pressure increase stopped. This process of making many small temperature adjustments proved the ability of the Chamber to respond to an issue by quickly lowering the helium supply temperature, which would stop the chamber pressure increase and any risk to the hardware. By following this method over the next seven days, the helium shrouds slowly warmed to the point where all of the air had liberated from the helium shrouds. At this point testing continued per the original profile without issue.

Because of this test, maximum leak rates were established that would prevent a repeat of these issues. In addition to the procedural fixes, a quick chamber pumpdown (Pre-Pathfinder Vacuum Functional) was also performed to verify adequate fixes were made to the leaking hardware.

Thermal Pathfinder Testing

With the JWST acceptance of the Chamber capabilities, the test series moved into the next phase of testing. This phase was less about the Chamber and its capabilities and more JWST hardware specific. Each of the three tests incorporated the Pathfinder (PF) hardware, which provided an OTIS simulator, into the chamber and helped reduce the risk to OTIS during its cryo-vacuum test. The three pathfinder tests were, Optical Ground Support Equipment (OGSE) 1, OGSE 2 and Thermal pathfinder.

Optical Ground Support Equipment 1 – 2015

OGSE 1 was the first cryo-vacuum test of the OTIS PF. The pathfinder contained two primary mirror segments as well as the secondary mirror so optical checkouts could be completed using specialized GSE. These optical tests are very sensitive to any vibrations so the typical facility dynamics needed to be characterized. To accomplish this, an initial facility dynamics test was performed by powering on and off the highbay air handlers, Air Flow Management System (AFMS), high vacuum pumps and helium systems while accelerometers placed around the chamber measured the change in vibrations seen by the pathfinder structure.

With the facility dynamics test complete the chamber pumpdown began. Following a brief GN2 sweep to help remove any moisture in the chamber a typical pumpdown was performed. The pumpdown was followed by the standard rate of rise (which showed a total gas load of about 1.8 Torr-l/second), leak check of any modified penetrations an off-gassing measurement, and initial optical checkouts. At this point, the helium shrouds started to cool at 0.5-2.0 K/hour as dictated by the OTIS thermal profile, with an ultimate steady state temperature of 31K. The conditioning of the LN2 shrouds to 90K followed shortly after the initial start of the helium cooldown. When the helium shrouds were at 120K, the cryopumps were isolated and the chamber was backfilled with helium and maintained within the 10^{-3} Torr range while the PF hardware cooled for an additional 10 days. Once the cooldown objectives were complete, the helium was removed and the high vacuum test points were performed. Prior to warmup a cryo-stable baseline of the facility dynamics was performed. This was similar to the ambient test but the helium flow to the shrouds and GSE was isolated.

With all objectives complete, the facility began warming the chamber. The air release from the shrouds was easily controlled using the same method as the previous test and was complete within a day. Following that, the remaining warmup and repress went without issue.

Optical Ground Support Equipment 2 – 2015

The second OGSE test profile was very similar to OGSE 1. The biggest difference was with the Pathfinder hardware. For OGSE 2 the Pathfinder was equipped with the flight Aft Optical Sensor. This was a key addition for the OTIS team to continue checkouts and verifications of their planned optical tests.

Testing began with another facility dynamics test. Similar to OGSE 1, this was performed by powering on and off the highbay air handlers, AFMS, high vacuum pumps and helium systems while accelerometers placed around the chamber measured the change in vibrations seen by the Pathfinder.

The Chamber was pumped down and the dynamics test was repeated followed by the standard rate of rise, leak checks and initial off-gassing assessment. Once that was complete, the cooldown of the LN2 and helium shrouds began. After 24-hours at high vacuum, the chamber was backfilled with helium and maintained at 5×10^{-3} Torr for the majority of the test. The facility continued to cool the GSE and helium shrouds until they achieved the steady state temperature of 32K where the OTIS team performed their steady state verifications. Once that was complete another dynamics test was performed before the chamber environment was brought back to ambient temperature and pressure.

Thermal Pathfinder – 2016

Following the successful completion of the two OGSE tests, it was time for the final dress rehearsal before the OTIS Cryo-Vacuum test. The Thermal Pathfinder would give both the facility and JWST test teams the opportunity to finalize the existing operations as well as check out new capabilities identified through fault tolerance reviews.

Like the previous OGSE tests, Thermal Pathfinder began with an ambient pressure and temperature dynamics test. Once that test was complete, the chamber was secured, and pumped down. In addition to the normal

penetration leak checks each of the facility LN2 and Helium shroud zones went through a leak check before ambient temperature testing with the PF continued. After the successful leak checks and completion of the ambient temperature objectives, another dynamics test was performed before cooldown preparations began.

As the helium shroud cooled at about 1.5K/hour, the LN2 shrouds were cooled to 90K and the cryopumping panels were cooled to 17K to act as a scavenger panel limiting the initial gas load that would have frozen out on the helium shrouds instead. As the Chamber and GSE cooled, adjustments were made real time to the helium inlet temperature to avoid any limits and constraints of the different pieces of PF hardware until cryo-stable was achieved at 20K and 3×10^{-7} Torr. Once the Chamber and the PF hardware were conditioned, the OTIS test team was able to perform their test points and while the facility maintained pressure and temperature stability. After all of the cryo-stable test points were complete, the most inclusive dynamics test was performed. In addition to the facility pumps and HVAC systems that were cycled on and off in previous tests, the GSE systems were cycled as well.

Warming of the helium shrouds and GSE followed the completion of the dynamics test. With the cryopumping panels held at 17K, the helium shrouds continued warming while air that was liberated from the shrouds was either pumped out or frozen to the cryopumping panels. Prior to warming the cryopumping panels, the roughing system was switched from normal power to the newly available roughing emergency backup power. With the roughing on emergency power in combination with the six turbopumps, the cryopumping panels gradually warmed over 24 hours until they had released all of the frozen air. Following the rest of the test profile, the chamber was brought back to ambient temperature followed by a GN2 repress and ventilation.

OTIS Cryo-Vacuum Testing (2017)

After the five years and nine tests, the Chamber and test teams were ready for the OTIS Cryo-Vacuum test. Every action and system had been exercised to the point that there would be nothing new once OTIS was installed.

With OTIS integrated into the chamber, the test team started the OTIS Cryo-Vacuum test with a final chamber walkthrough. All hardware connections were verified one last time and the chamber cleanliness was checked before the doors were latched and pumpdown could begin. The chamber roughing system was brought online lowering the pressure until the chamber was easily transitioned to high vacuum where the facility team performed a rate of rise (total gas load was measured to be about 0.5 Torr-l/Second), a chamber leak check, and conditioned the internal scavenger panels. After this, the OTIS team began their ambient temperature operations. After close to 10 days, the OTIS team was ready to continue into the cooldown phase of the test. The helium shrouds started cooling per the OTIS thermal profile at 1.0-1.5K/hour until the helium average was about 260K. This planned delay limited any impact to the helium shroud cool down rates. In addition to the LN2 shrouds, the cryopumping panels were also conditioned to 20K lowering the chamber pressure to the low 10^{-7} Torr range. This can be seen below in Figure 3.

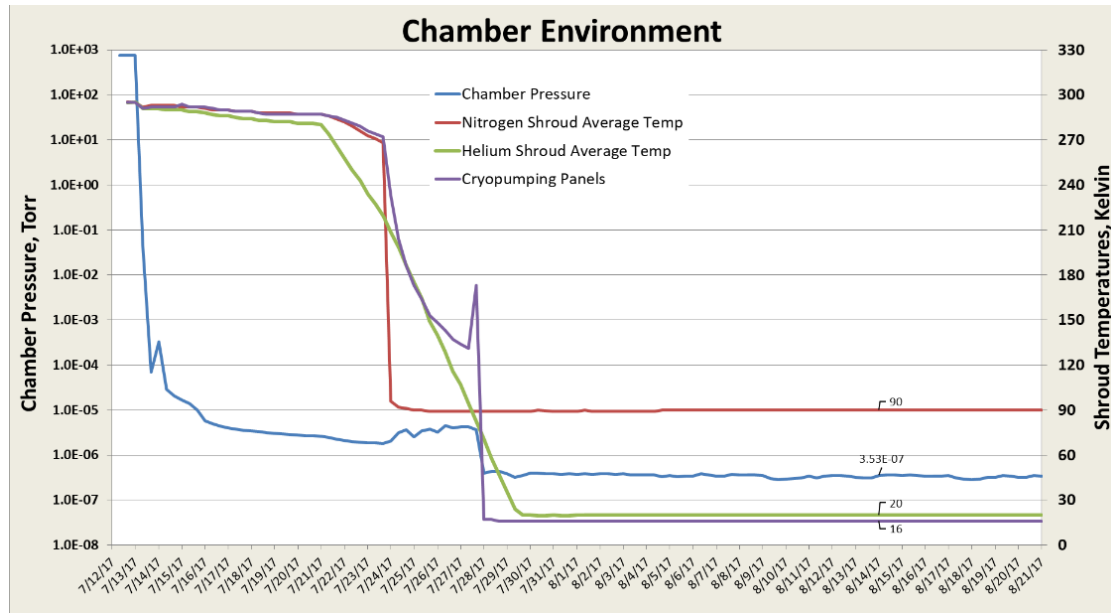


Figure 3: OTIS Cryo-Vacuum Chamber Parameters – Pumpdown to Steady State

Just as the flight hardware was approaching its steady state temperatures, the Houston area was preparing for the approaching Hurricane Harvey. The test team had an established hurricane plan and initial preparations were started. Emergency systems were functionally checked and the LN2 and backup diesel tanks were completely filled. Heavy rains in the JSC area arrived shortly after Harvey made landfall to the south of Houston causing severe flooding in and around the Houston area. The facility suffered roof leaks in many test operation locations but they could be contained, minimizing the impact to the test area. The OTIS test team rearranged some of their steady state test points but continued testing and no objectives were compromised due to the storm and subsequent flooding.

With the test weathering the storm, the OTIS team was able to complete their steady state test objectives and move to warm up operations. The first action was to subject the flight hardware to a thermal distortion test. To accomplish this test helium shrouds were warmed to 100K before being cooled back to 75K and held while OTIS completed optical testing. Once that objective was complete, the warm up continued until the shroud average was 140K at which time they were stabilized to warm the cryopumping panels. Using the method perfected in the previous tests the cryopumping panels were easily warmed without issue. At that point, the helium shrouds resumed their warmup back to ambient temperature as show below in Figure 4.

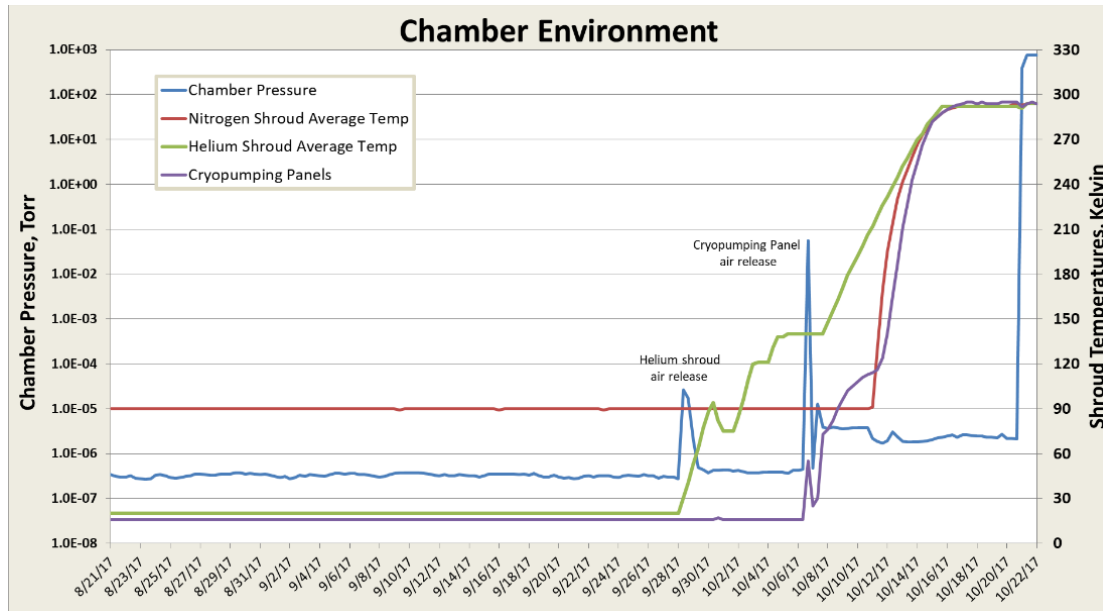


Figure 4: OTIS Cryo-Vacuum Chamber Parameters – Steady State to Repress

With the chamber back at ambient temperature, the OTIS team performed their final checkouts at high vacuum. With all of the cryo-vacuum objectives complete, the chamber was repressed using GN2 and then ventilated thus completing the OTIS Cryo-Vacuum test.

Conclusion

The cryo-vacuum test of the James Webb Telescope's OTIS hardware can easily trace its success to the series of tests that were performed long before flight hardware arrived. By performing numerous tests throughout the integration process, the facility was able to limit or eliminate major risks to the hardware. Brand new systems were verified and perfected while operators gained the experience and confidence to operate them.

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